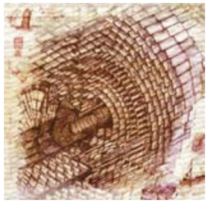

DC-DC Power Conversion for the CMS Pixel Phase I Upgrade

Katja Klein

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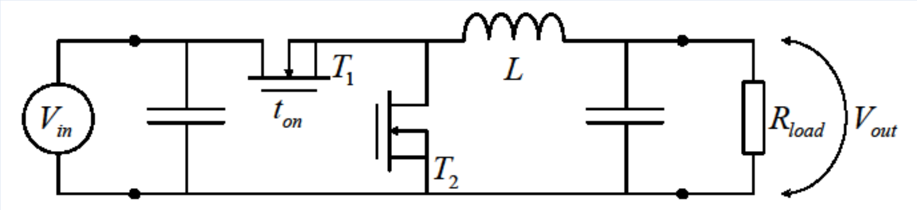
with input from: W. Bertl, A. Schultz von Dratzig,
L. Feld, W. Karpinski, J. Merz, J. Sammet, M. Wlochal

ACES 2011
March 9th, 2011

Introduction

- Exchange of pixel detector around 2017 → number of readout chips will increase by factor 1.9 → unacceptable power losses in cable trays
- Compatibility with existing power supply chain desirable
  → **DC-DC buck converters with conversion ratio of 2-3**



Idea: $P = U \cdot I = (rU) \cdot (I/r)$ with conversion ratio $r > 1$

Duty cycle $D = t_{on}/T$; $1/D = I_{out}/I_{in} = V_{in}/V_{out} = r$

Output voltage regulation through PWM

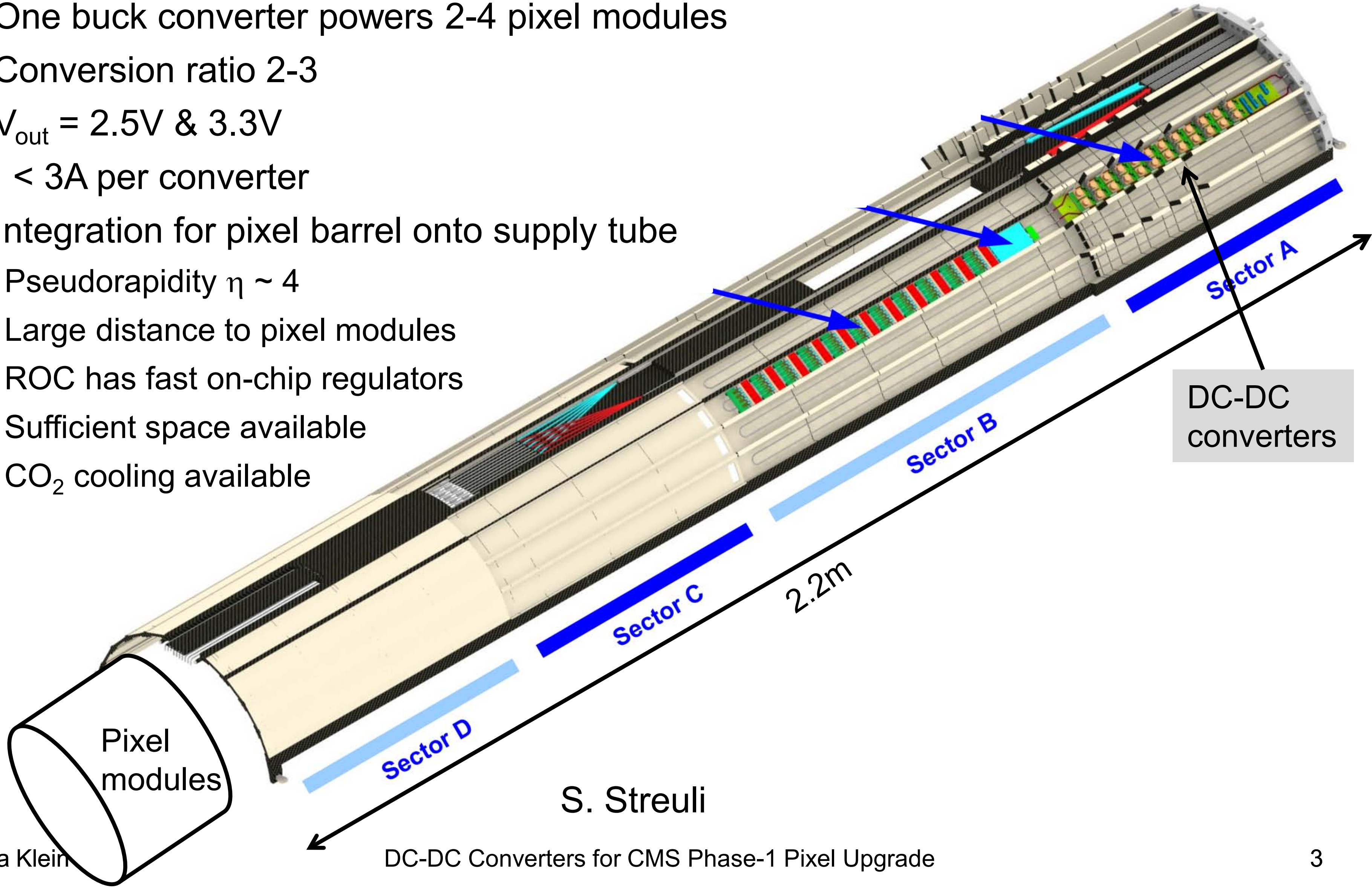
Challenges

- Radiation tolerance of high voltage (~12V) power transistors
- Magnetic field tolerance → air-core inductor
- Minimization and control of noise emissions (conductive & radiated)
- Maximization of efficiency
- Minimization of material and size

DC-DC Converters for the Pixel Upgrade

- One buck converter powers 2-4 pixel modules
- Conversion ratio 2-3
- V_{out} = 2.5V & 3.3V
- I < 3A per converter
- Integration for pixel barrel onto supply tube

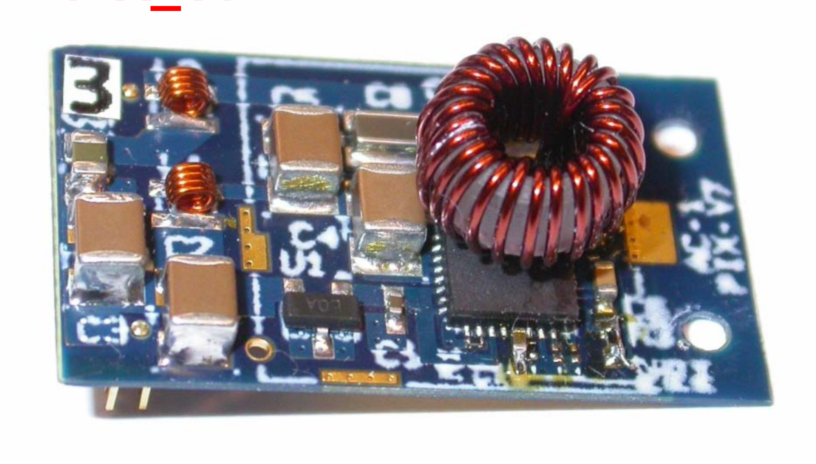
✓ Pseudorapidity $\eta \sim 4$
✓ Large distance to pixel modules
✓ ROC has fast on-chip regulators
✓ Sufficient space available
✓ CO_2 cooling available

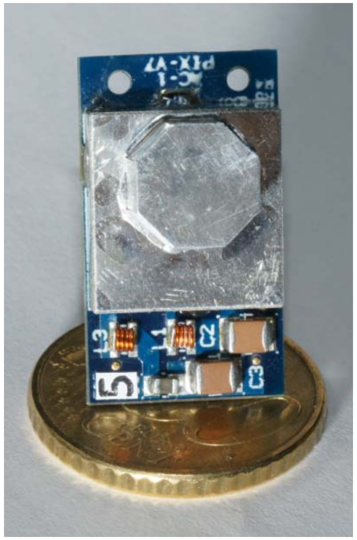


S. Streuli

DC-DC Buck Converter Development

PIX_V7





M = 2.3g

A = 28×16 mm^2

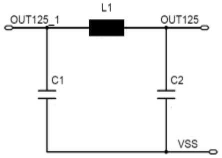
Buck ASIC development:
10. 3., Technologies 1

ASIC: AMIS2 by CERN
Iout < 3A
Vin < 12V
Vout configurable; 2.5V & 3.3V
fs configurable, e.g. 1.3MHz

PCB:
2 copper layers a 35µm
0.3mm thick
Large ground area on bottom for cooling

Toroidal inductor:
L = 450nH
$R_{DC} = 40m\Omega$

Pi-filters at in- and output



Shield (optimized for space constraints)

Design guidelines from CERN group have been implemented.

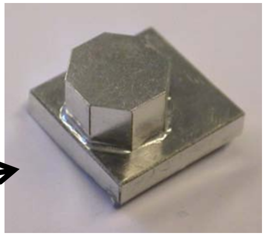
The Shield

The shield has three functions:

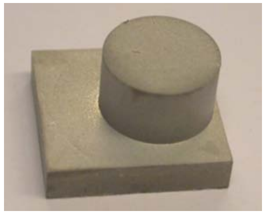
1) to shield radiated emissions from inductor
2) to reduce conducted noise by means of segregation between noisy and quiet parts of board (less coupling)
3) to provide cooling contact for coil through its solder connection to PCB, since cooling through contact wires not sufficient (see later)

We are currently investigating several technologies:

- Aluminium shields of various thicknesses (50µm, 150µm)

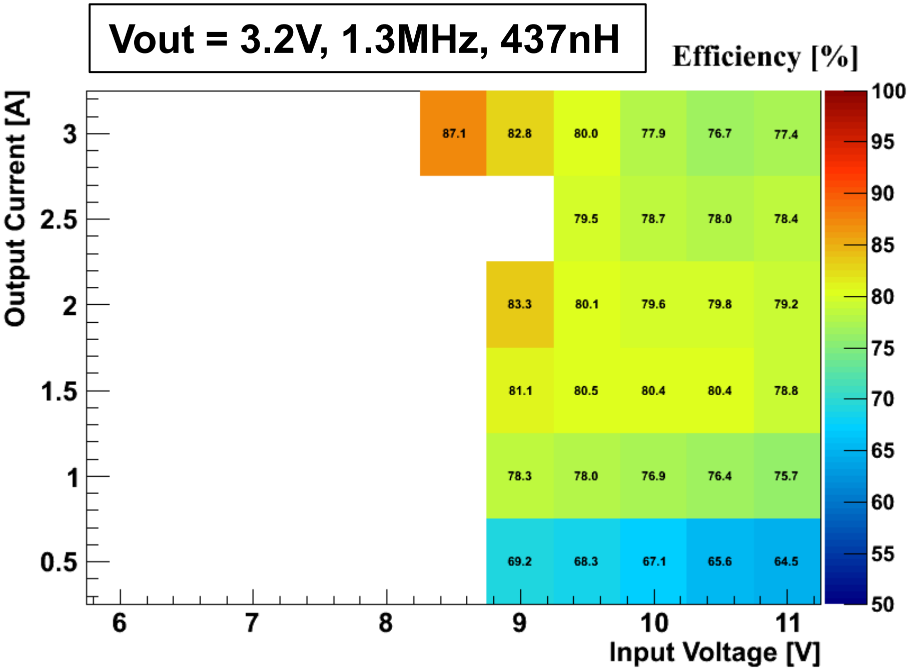


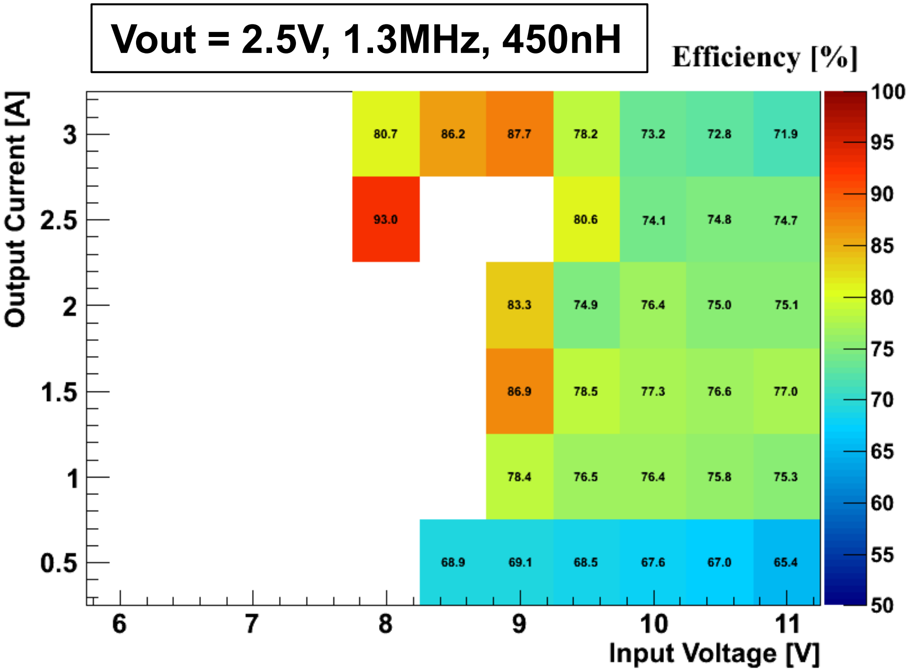
- Plastic shields (PEEK) coated with a metall layer (outside, inside & outside)
  - Aluminium sputtered (5 or 10µm)
  - Copper/tin sputtered (5 or 10µm)
  - Copper, galvanic deposition (20µm)
  - Parylene coating of whole PCB ...



We are also in contact with industry to find industrial affortable solutions (deep drawing, forming with water pressure, ...)

Efficiency





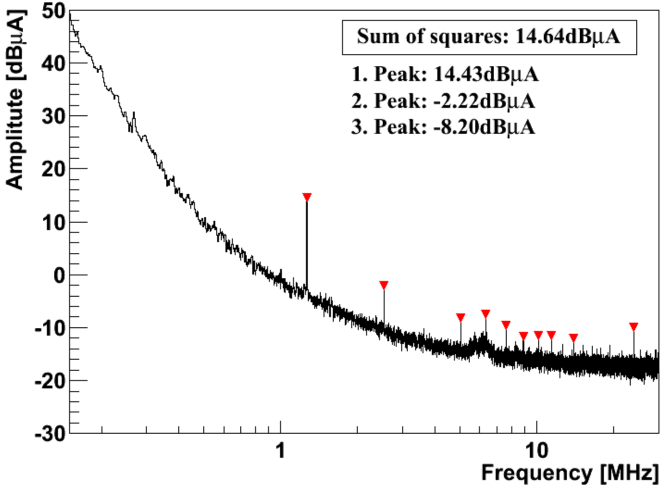
→ **Efficiencies are around 75%** (acceptable)

→ Expected to increase for AMIS4 ASIC

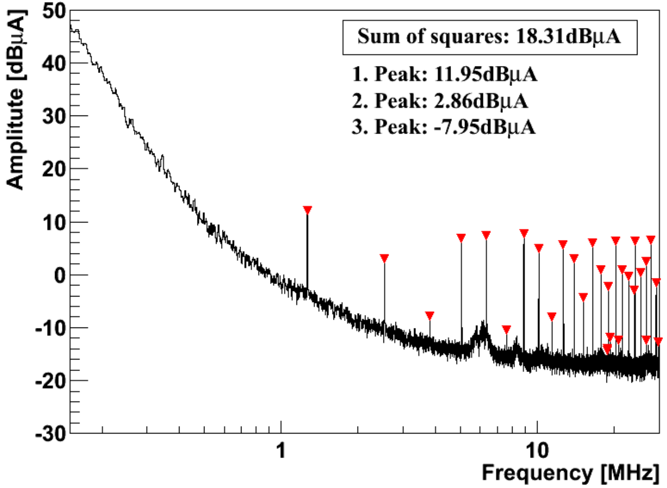
→ Inductance and switching frequency chosen as to reach highest efficiency

Conductive Noise at Converter Output

Differential Mode, no shield

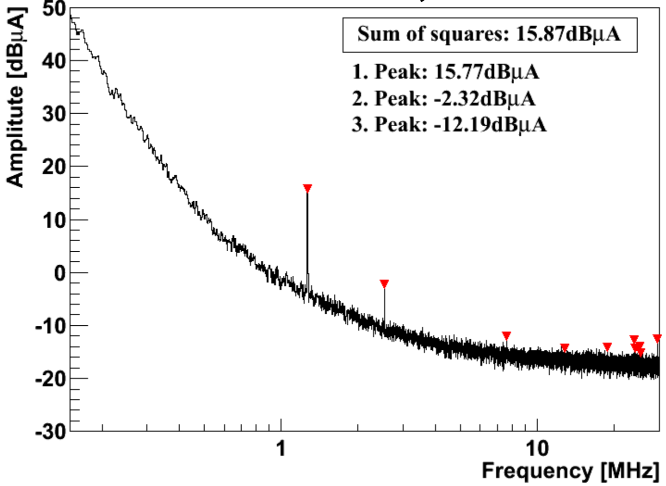


Common Mode, no shield

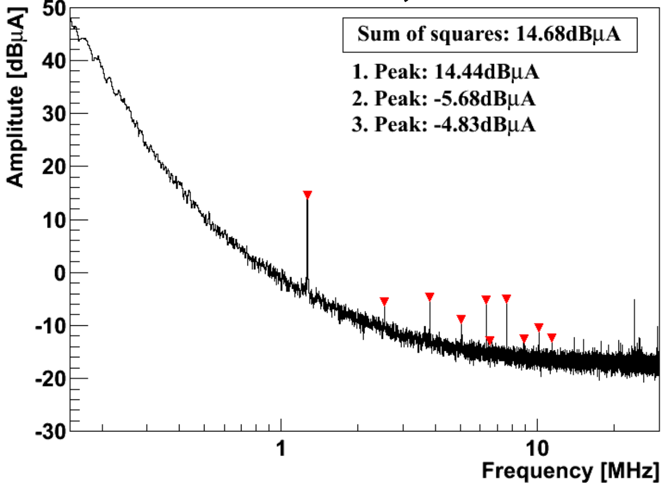


PIX_V7
Vout = 3.3V
Vin = 10V
fs = 1.3MHz
L = 450nH

Differential Mode, with shield



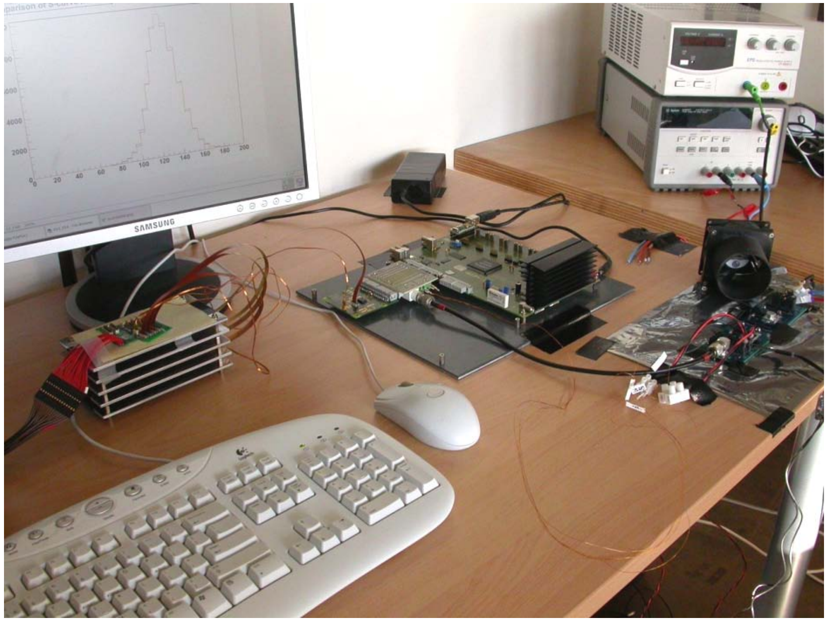
Common Mode, with shield

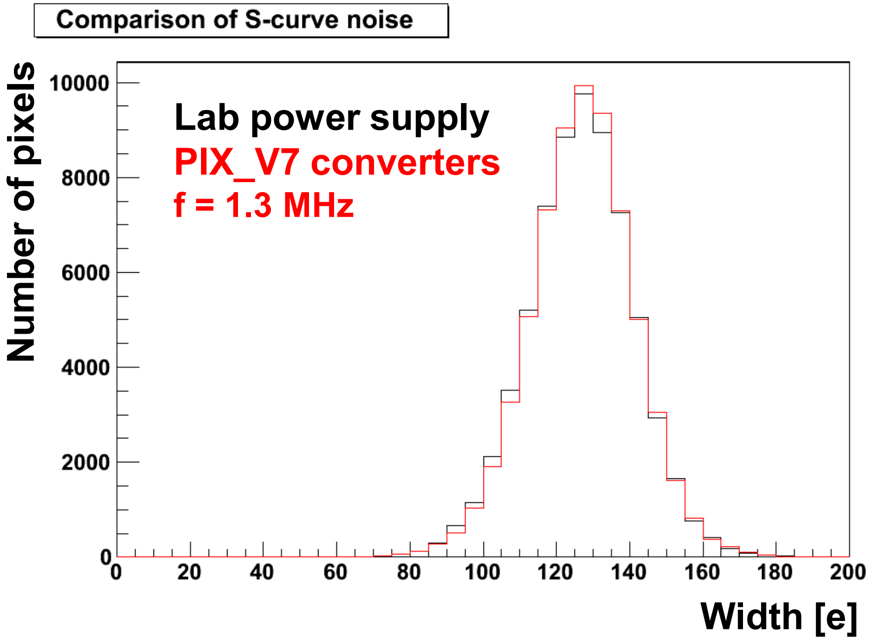


Shield most effective above ~ 2-3 MHz → large reduction of CM, less red. for DM

Conductive Noise

- Tests with pixel modules have to tell if noise is acceptable & what frequency is preferred!
- Measurement of S-curve with and without DC-DC converters
- Width of S-curve is taken as noise figure
- Pixel modules seem to be rather insensitive to ripple from PIX_V7 converters
- Work in progress ...



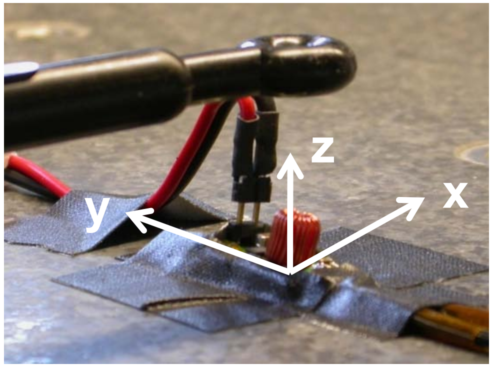


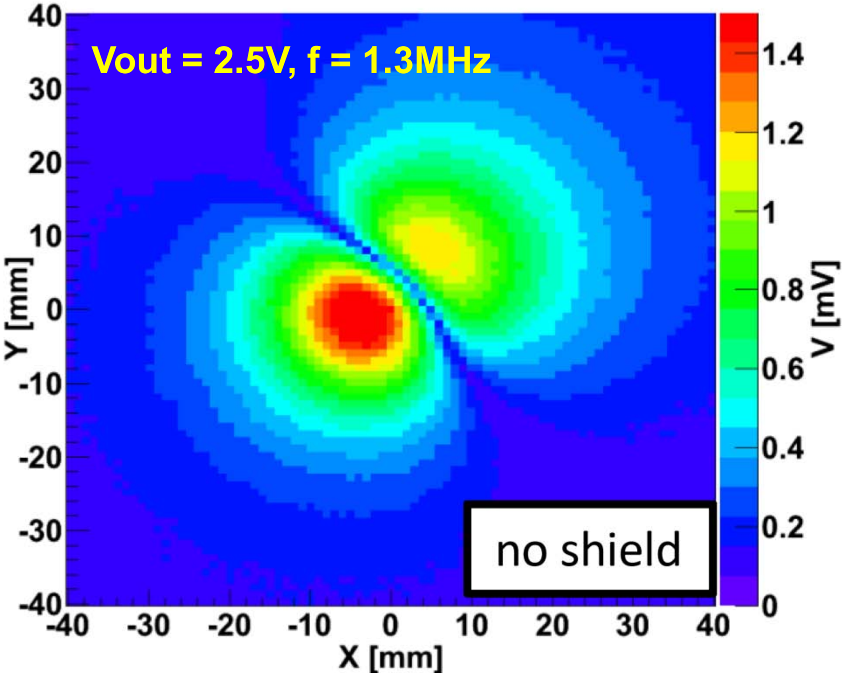
Radiated Noise Emissions

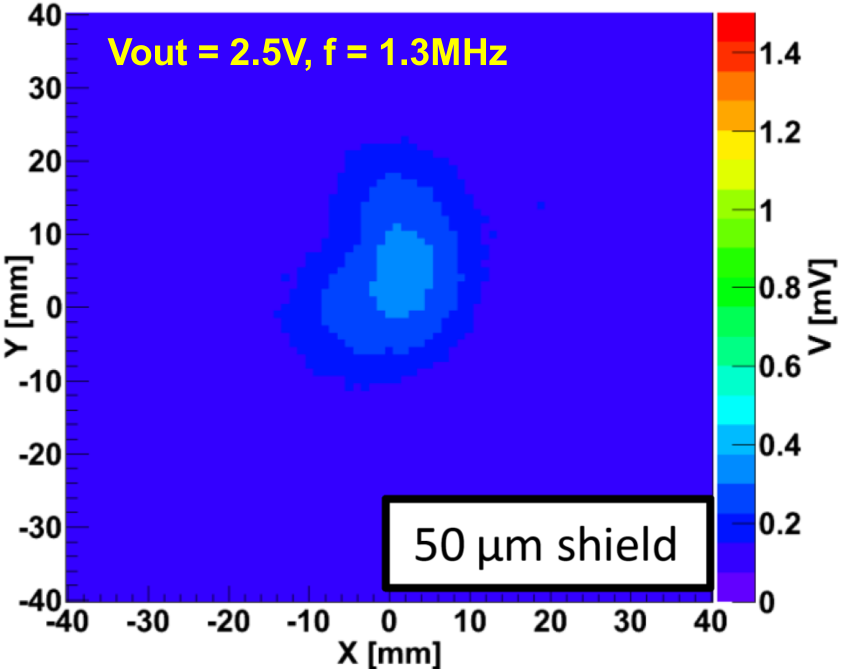
Field measured with pick-up probe ~ 1.5mm above coil

→ Both 150μm & 50μm Aluminium shields are very effective

→ Plastic shields coated with 10-20μm Alu or Cu are much less effective

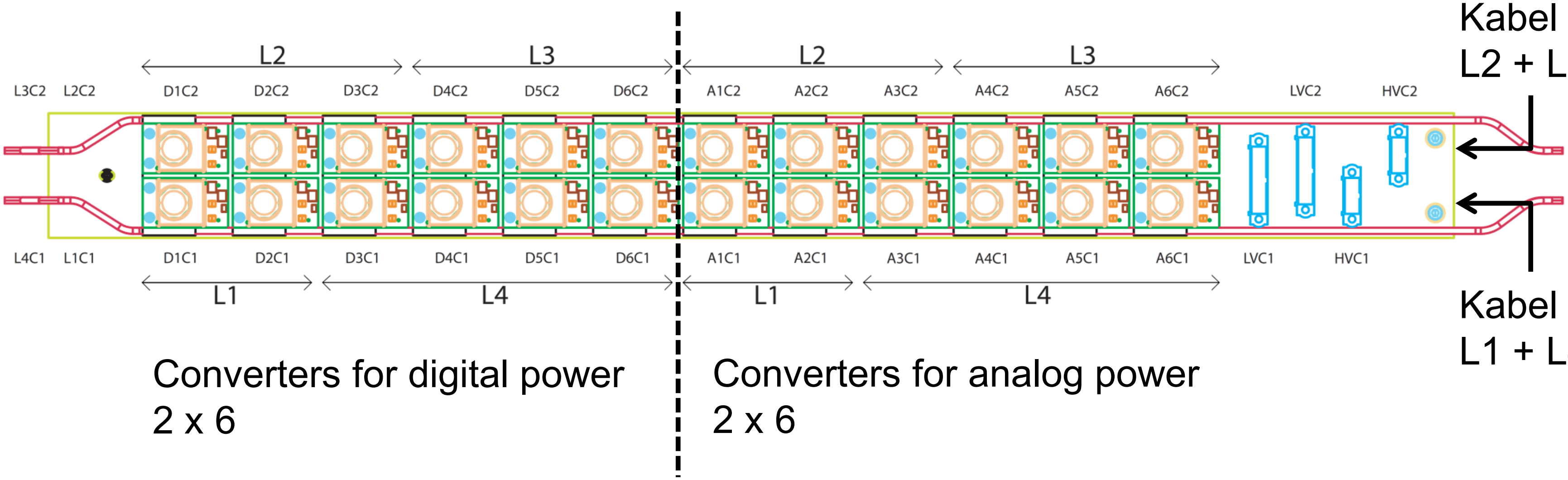






Electrical Integration

Section A of supply tube:



Kabel 2:
L2 + L3

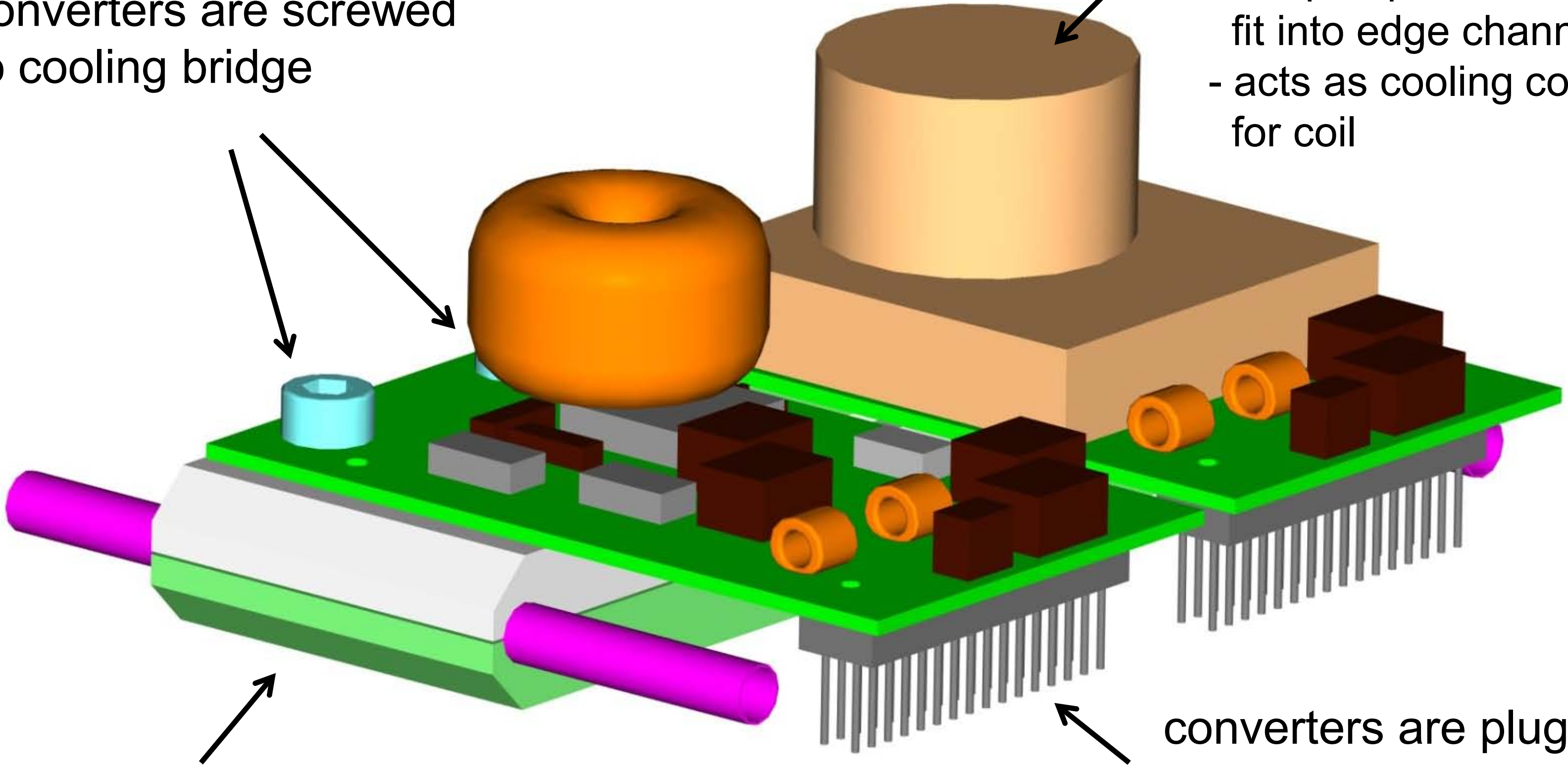
Kabel 1:
L1 + L4

Converters for digital power
2 x 6

Converters for analog power
2 x 6

- Up to 24 converters per channel
- 6 analog & 6 digital converters per cable and power supply
- Per converter: 2 or 2-3 or 4 or 4 modules of layer 1 / 2 / 3 / 4
- Max. current per converter: 2.8A (for $L = 2 \times 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$)
- Large digital current changes due to orbit gaps (up to 1A ↔ 2.8A)
- Bus PCB is under development

Mechanical & Thermal Integration



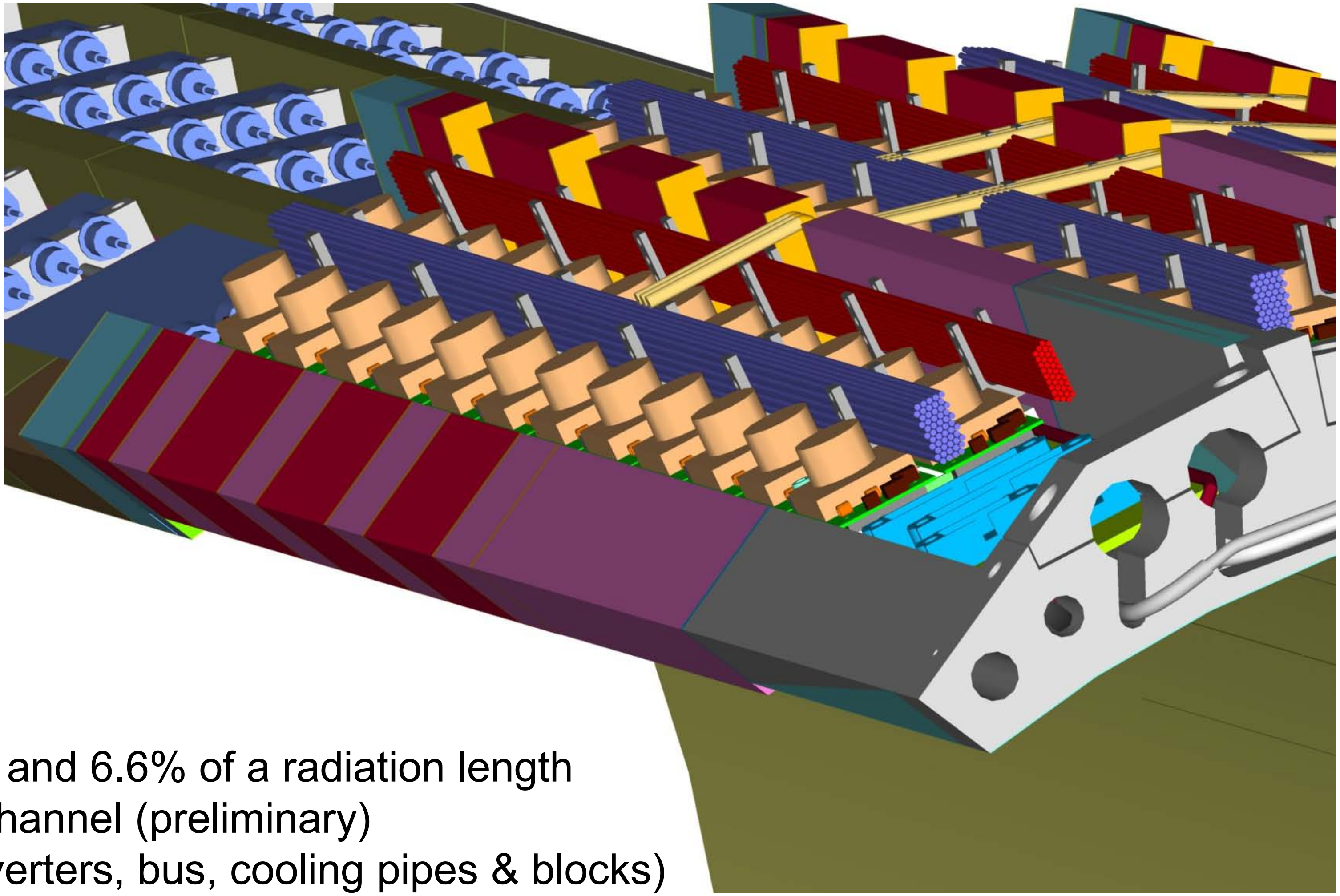
Electrical shielding
- shape optimized to fit into edge channels
- acts as cooling contact for coil

converters are screwed to cooling bridge

cooling bridge is glued to bus PCB (on a jig)

converters are plugged to bus PCB

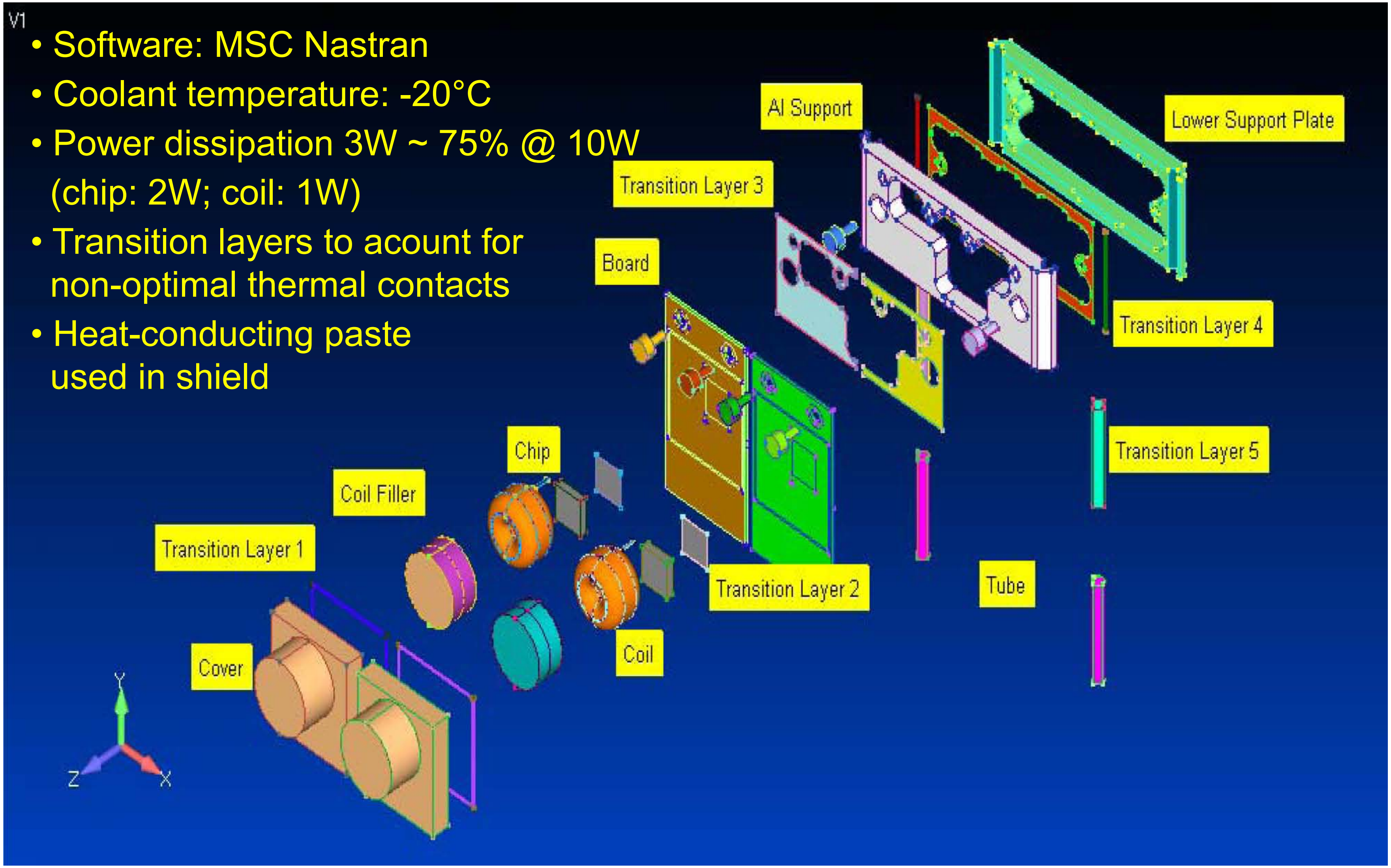
Mechanical & Thermal Integration



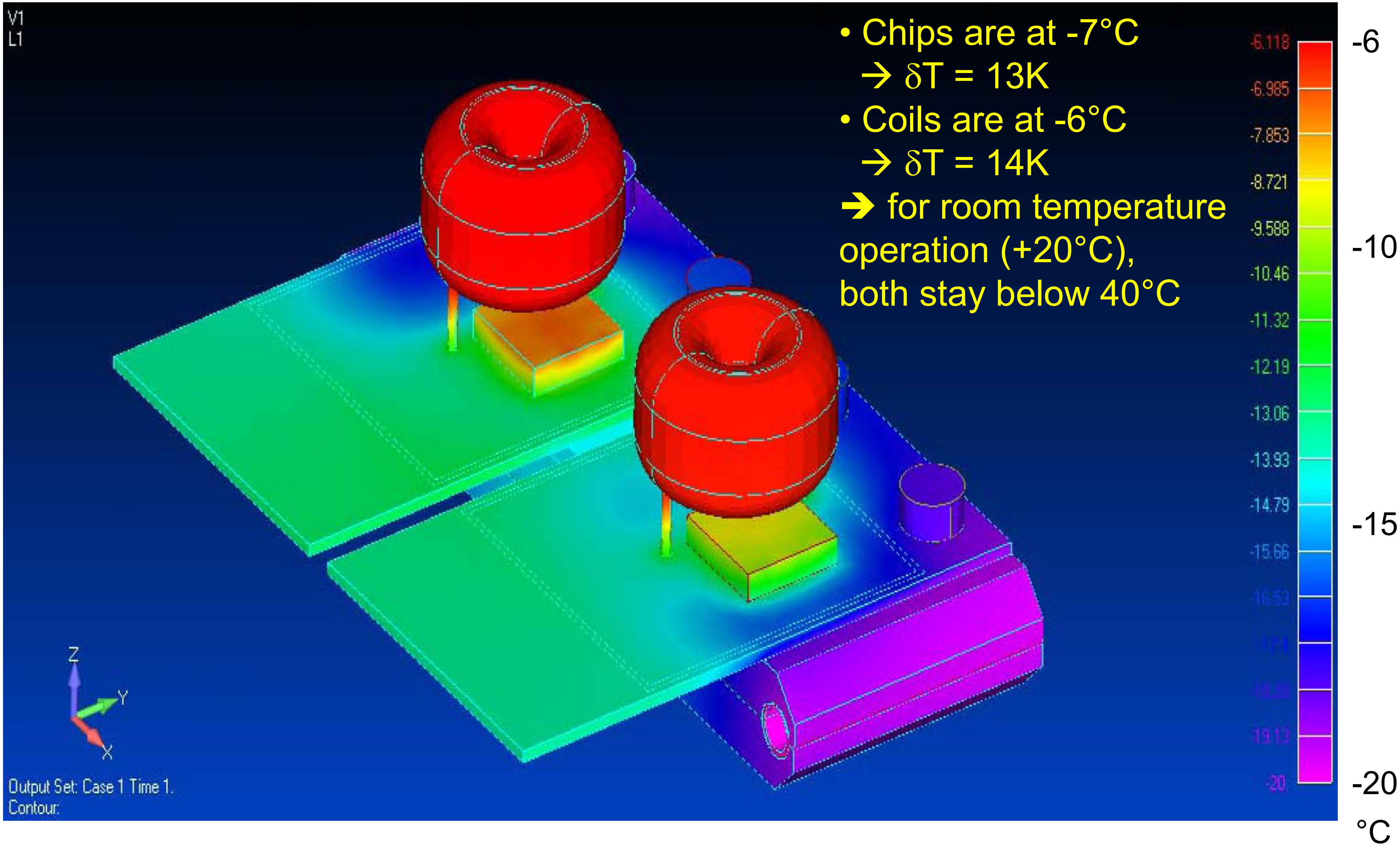
194g and 6.6% of a radiation length
per channel (preliminary)
(converters, bus, cooling pipes & blocks)

Thermal FE-Simulation

- Software: MSC Nastran
- Coolant temperature: -20°C
- Power dissipation 3W ~ 75% @ 10W (chip: 2W; coil: 1W)
- Transition layers to acount for non-optimal thermal contacts
- Heat-conducting paste used in shield



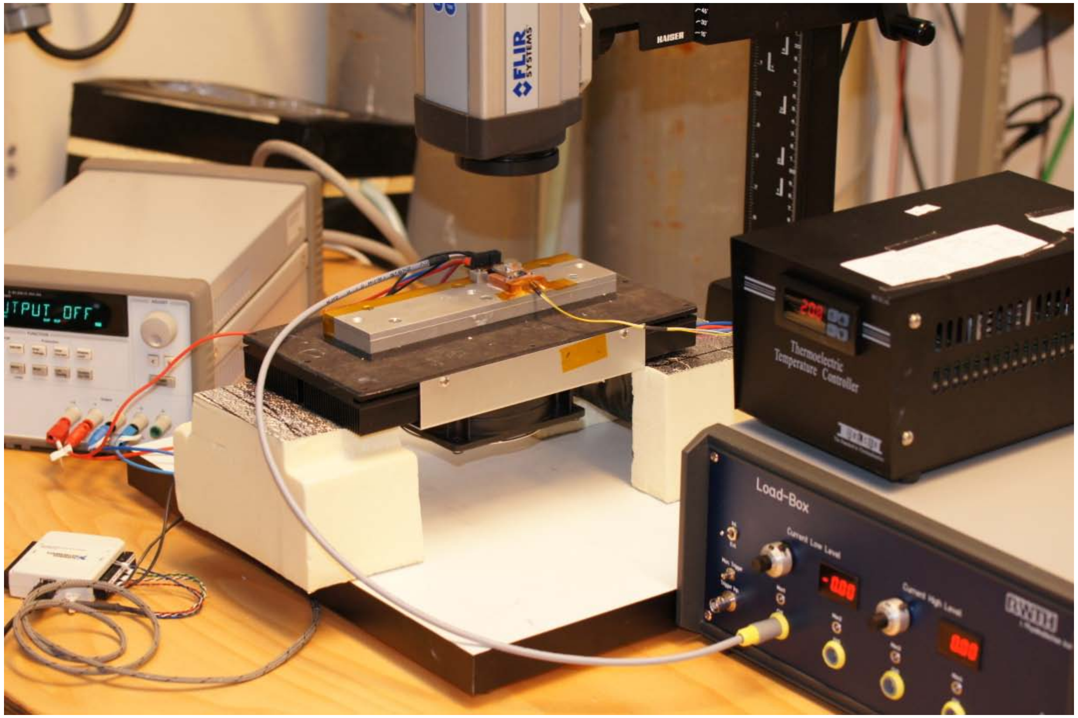
Thermal FE-Simulation

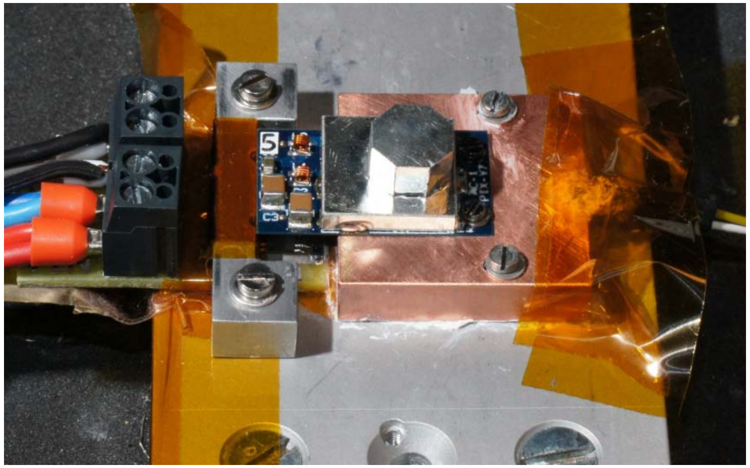


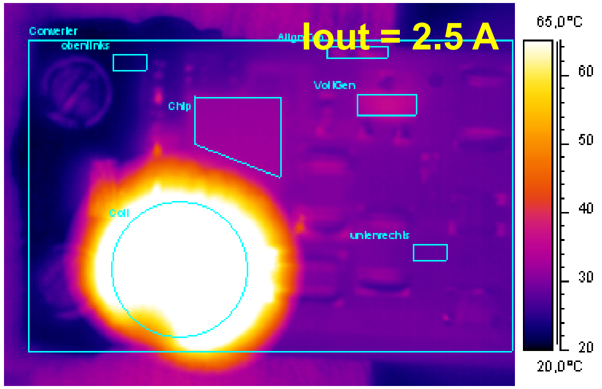
- Chips are at -7°C
  → δT = 13K
- Coils are at -6°C
  → δT = 14K

➔ for room temperature operation (+20°C), both stay below 40°C

Thermal Measurements

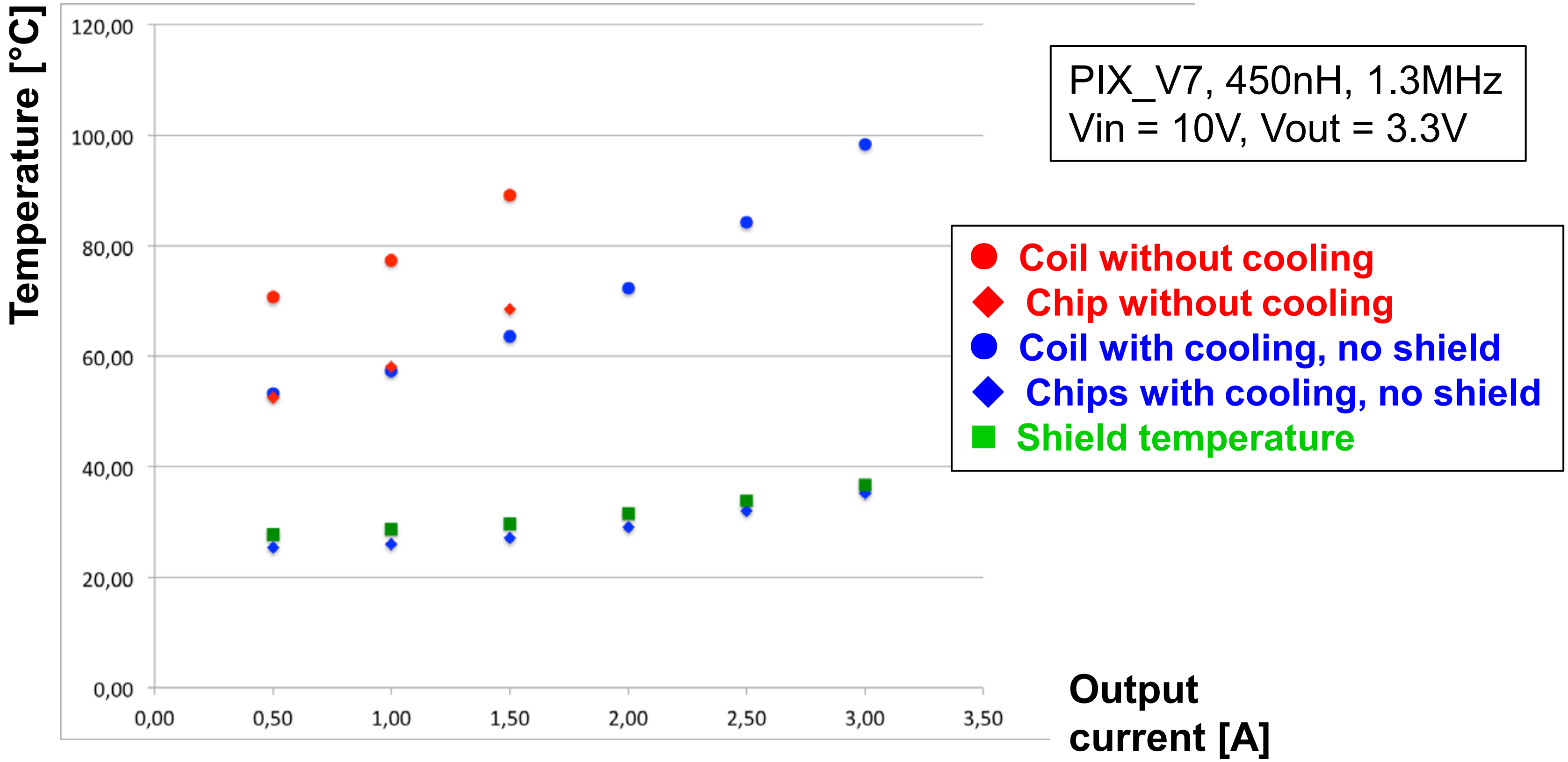






- To cross-check simulations
- Peltier element set to +20°C
- Peltier regulates on external sensor that is fixed to copper block
- Temperate of coil, chip and PCB versus output current

Thermal Measurements



PIX_V7, 450nH, 1.3MHz
Vin = 10V, Vout = 3.3V

→ Converters need to be cooled

→ Cooling of chips via backside of PCB is very effective

→ Coil needs to be connected to cooling contact (shield)

→ Good agreement with FE-simulations

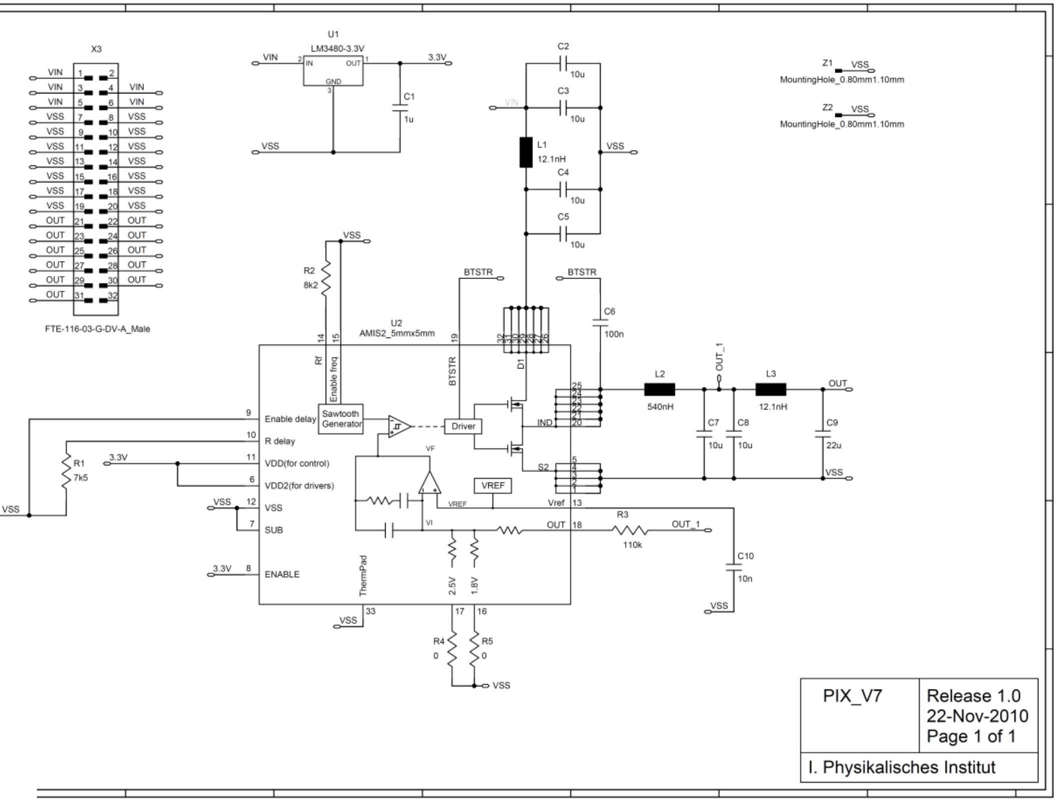
Summary & Outlook

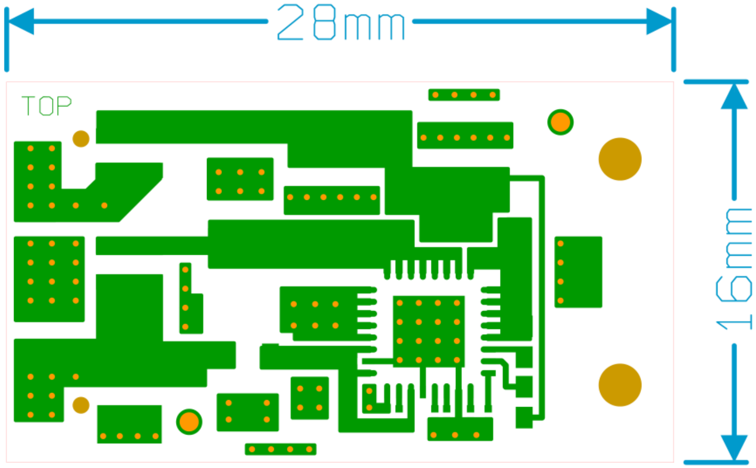
- Low noise converters with reasonable efficiency in hands
- Large progress with mechanical, electrical and thermal integration
- Cooling of converters (chip and coil) under control

- Industrialization of coil and shield production
- Further study of sensitivity of pixel modules to ripple from DC-DC converters
- Production and test of bus PCB, thermal tests with cooling bridge, ...
- Turn next ASICs (AMIS3, AMIS4) into converters

Back-up Slides

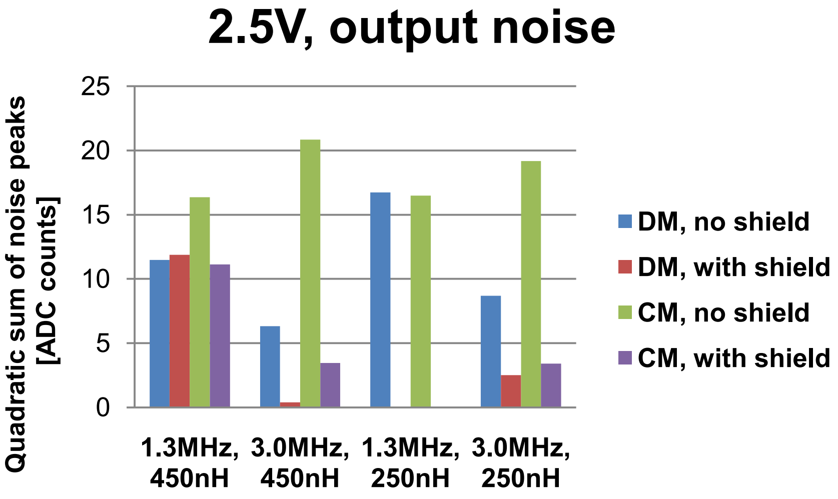
DC-DC Buck Converter Development

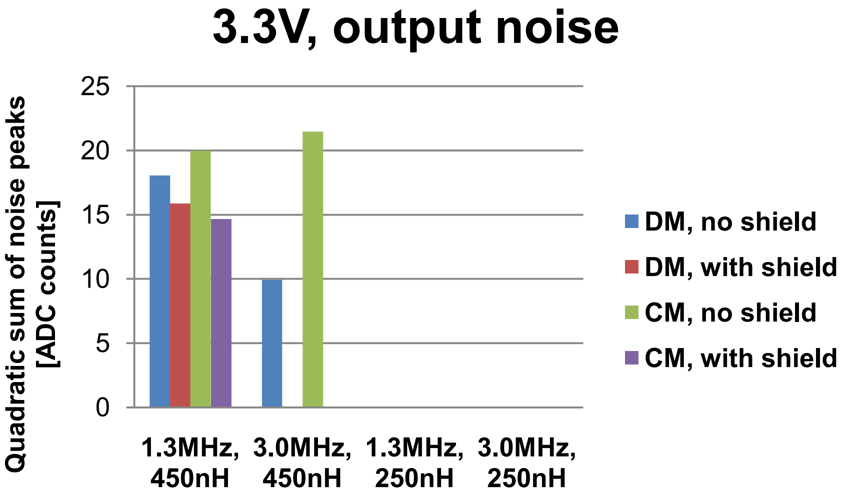




Design guidelines from CERN group have been implemented.

Conductive Noise

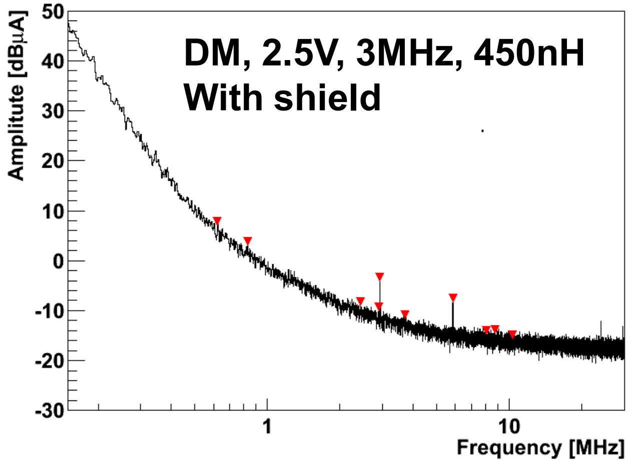

2.5V, output noise


3.3V, output noise

The conductive noise at the input and output has been studied under various conditions:

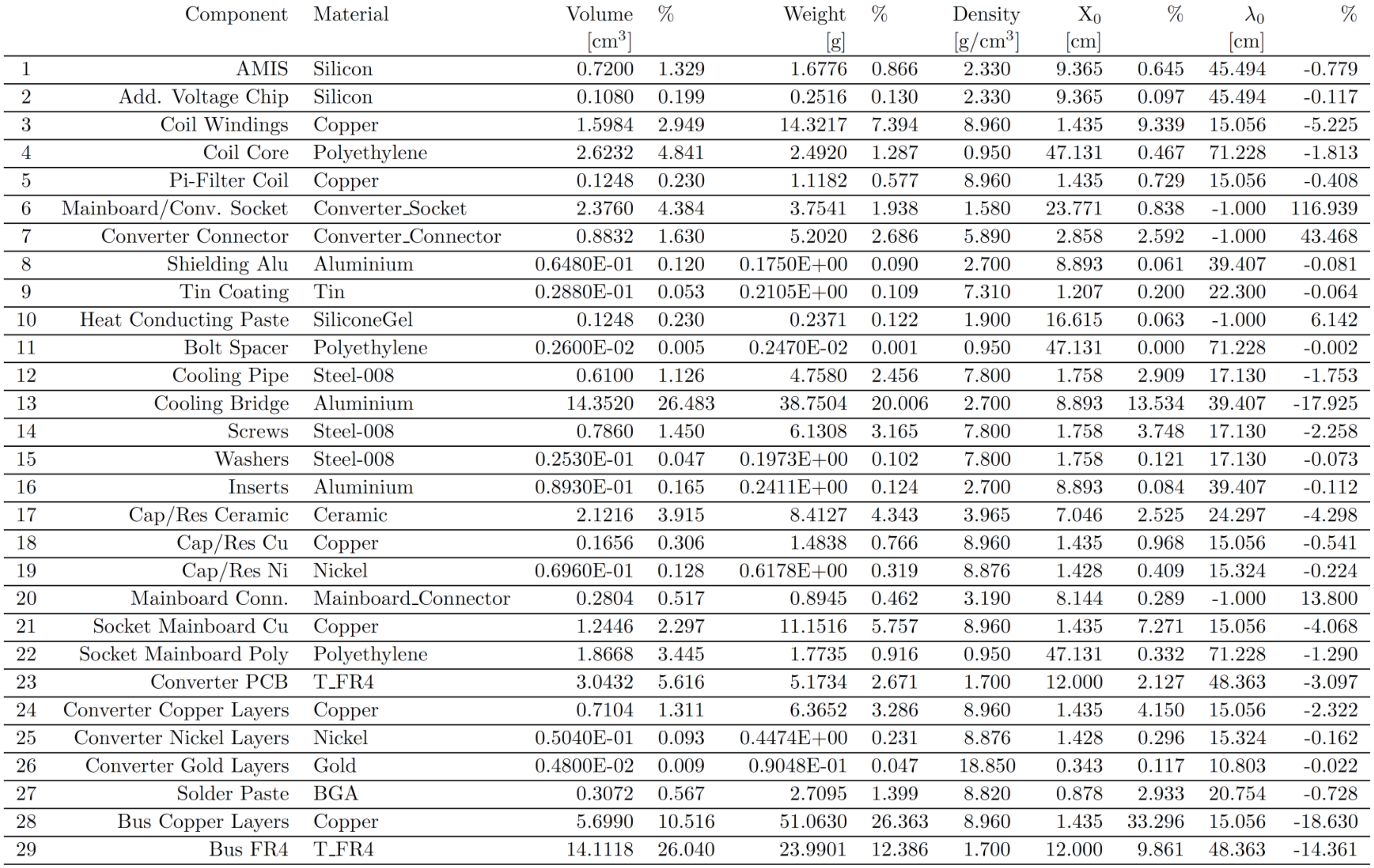
→ Shield is more effective for switching frequency of (e.g.) 3MHz

→ Larger DM noise for lower inductance


DM, 2.5V, 3MHz, 450nH
With shield

Material Budget of one Channel

Material of 24 converters, bus PCB, cooling bridges & pipes for 1 supply tube channel:



	Component	Material	Volume [cm^3]	%	Weight [g]	%	Density [g/cm^3]	X_0 [cm]	%	λ_0 [cm]	%
1	AMIS	Silicon	0.7200	1.329	1.6776	0.866	2.330	9.365	0.645	45.494	-0.779
2	Add. Voltage Chip	Silicon	0.1080	0.199	0.2516	0.130	2.330	9.365	0.097	45.494	-0.117
3	Coil Windings	Copper	1.5984	2.949	14.3217	7.394	8.960	1.435	9.339	15.056	-5.225
4	Coil Core	Polyethylene	2.6232	4.841	2.4920	1.287	0.950	47.131	0.467	71.228	-1.813
5	Pi-Filter Coil	Copper	0.1248	0.230	1.1182	0.577	8.960	1.435	0.729	15.056	-0.408
6	Mainboard/Conv. Socket	Converter_Socket	2.3760	4.384	3.7541	1.938	1.580	23.771	0.838	-1.000	116.939
7	Converter Connector	Converter_Connector	0.8832	1.630	5.2020	2.686	5.890	2.858	2.592	-1.000	43.468
8	Shielding Alu	Aluminium	0.6480E-01	0.120	0.1750E+00	0.090	2.700	8.893	0.061	39.407	-0.081
9	Tin Coating	Tin	0.2880E-01	0.053	0.2105E+00	0.109	7.310	1.207	0.200	22.300	-0.064
10	Heat Conducting Paste	SiliconeGel	0.1248	0.230	0.2371	0.122	1.900	16.615	0.063	-1.000	6.142
11	Bolt Spacer	Polyethylene	0.2600E-02	0.005	0.2470E-02	0.001	0.950	47.131	0.000	71.228	-0.002
12	Cooling Pipe	Steel-008	0.6100	1.126	4.7580	2.456	7.800	1.758	2.909	17.130	-1.753
13	Cooling Bridge	Aluminium	14.3520	26.483	38.7504	20.006	2.700	8.893	13.534	39.407	-17.925
14	Screws	Steel-008	0.7860	1.450	6.1308	3.165	7.800	1.758	3.748	17.130	-2.258
15	Washers	Steel-008	0.2530E-01	0.047	0.1973E+00	0.102	7.800	1.758	0.121	17.130	-0.073
16	Inserts	Aluminium	0.8930E-01	0.165	0.2411E+00	0.124	2.700	8.893	0.084	39.407	-0.112
17	Cap/Res Ceramic	Ceramic	2.1216	3.915	8.4127	4.343	3.965	7.046	2.525	24.297	-4.298
18	Cap/Res Cu	Copper	0.1656	0.306	1.4838	0.766	8.960	1.435	0.968	15.056	-0.541
19	Cap/Res Ni	Nickel	0.6960E-01	0.128	0.6178E+00	0.319	8.876	1.428	0.409	15.324	-0.224
20	Mainboard Conn.	Mainboard_Connector	0.2804	0.517	0.8945	0.462	3.190	8.144	0.289	-1.000	13.800
21	Socket Mainboard Cu	Copper	1.2446	2.297	11.1516	5.757	8.960	1.435	7.271	15.056	-4.068
22	Socket Mainboard Poly	Polyethylene	1.8668	3.445	1.7735	0.916	0.950	47.131	0.332	71.228	-1.290
23	Converter PCB	T_FR4	3.0432	5.616	5.1734	2.671	1.700	12.000	2.127	48.363	-3.097
24	Converter Copper Layers	Copper	0.7104	1.311	6.3652	3.286	8.960	1.435	4.150	15.056	-2.322
25	Converter Nickel Layers	Nickel	0.5040E-01	0.093	0.4474E+00	0.231	8.876	1.428	0.296	15.324	-0.162
26	Converter Gold Layers	Gold	0.4800E-02	0.009	0.9048E-01	0.047	18.850	0.343	0.117	10.803	-0.022
27	Solder Paste	BGA	0.3072	0.567	2.7095	1.399	8.820	0.878	2.933	20.754	-0.728
28	Bus Copper Layers	Copper	5.6990	10.516	51.0630	26.363	8.960	1.435	33.296	15.056	-18.630
29	Bus FR4	T_FR4	14.1118	26.040	23.9901	12.386	1.700	12.000	9.861	48.363	-14.361

→ 194g and 6.6% of a radiation length per channel (acceptable)

Electrical Integration

Interaction Piont

Shell	Position in z	Slot															
		1		2		3		4		5		6		7		8	
BPI	1	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2
BPI	2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2
BPI	3	L4C1	L2C2	L4C1		L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	
BPI	4	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2
BPI	5	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2
BPI	6	L4C1		L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1		L4C1	L3C2	L4C1	L3C2

Shell	Position in z	Slot															
		1		2		3		4		5		6		7		8	
BPO	1	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2
BPO	2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2	L1C1	L2C2
BPO	3	L4C1	L2C2	L4C1		L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	L2C2	L4C1	
BPO	4	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2
BPO	5	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2
BPO	6	L4C1		L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1	L3C2	L4C1		L4C1	L3C2	L4C1	L3C2

Thermal FE-Simulation

- Support Plates: Aluminum **200 W/m/K**
- Tubes: Stainless Steel (316L) **18.8 W/m/K**
- Coils: Copper **390 W/m/K**
- Chips: Silicon **20 W/m/K**
- Screws: Stainless Steel **13 W/m/K**
- Coil Filler: Conductive Glue: **22 W/m/K**

- Transition Layer Between Support Plates: Assumed 50 % Contact **100 W/m/K**
- Transition Layer Around Tubes: Assumed 95 % Contact **190 W/m/K**
- Transition Layer Underneath Boards: Some Conductive Plastic **20 W/m/K**
- Transition Layer Underneath Chips: 32 Contacting Strips (**0.25 mm** Dia) and a **∅2 mm** Solder Patch resulting in **4.1 W/m/K**
- Transition Layer Underneath Cover: At 4 Locations Solder **3 mm** Wide, **1.5 mm** High, **1.4 W/m/K**

- Boards:
  The Board Consists of a Glass Fiber Composite Coated with two Layers of Copper Foil. The Thickness of the Composite is **0.3 mm** and of the Foil **0.035 mm**. At Several Locations there are Feedthroughs from the Upper to the Lower Foils. The Upper Foil covers 70 % of the Total Area and the Lower 100 %. The Fraction of the Feedthroughs is 1 % of the Total Area.

  in plane: 63W/m/K
  accross plane: 5W/m/K

- Plastic Cover:
  The Cover Consists of a Plastic Body coated with Layers of Aluminum Foil. The Thickness of the Plastic is **0.3 mm** and of the Foil **0.05 mm**. The Foils Cover the Plastic Totally. This leads to

  in plane: 55W/m/K
  accross plane: 0.2W/m/K

Thermal FE-Simulation